Chapter 23

Fracture and Toughening

Fracture behavior
Fracture testing
Impact/Fatigue
Toughening

Failure or fracture

- failure [破碎, 破斷] ~ rupture by exceedingly large stress
- fracture [破壞] ~ failure by crack propagation

- micromechanism of fracture
  - chain scission or slip?
  - Upon stress,

    1. chain slip (against Xtal, Xlinking, entangle)

    2a. crazing/yielding or

    2b. chain scission (early)
    when high X_c, low M_c, low M_e

    3. then chain scission

    4. voiding → crack → fracture

- effect of MM (on strength)
  - M = 6 – 8 M_e?
  - MM should be much higher than M_e.

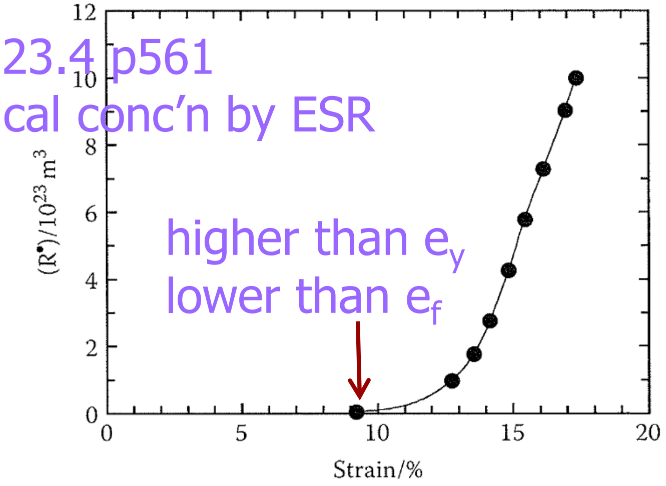


Fig 23.4 p561
radical conc'n by ESR

higher than e_y
lower than e_f

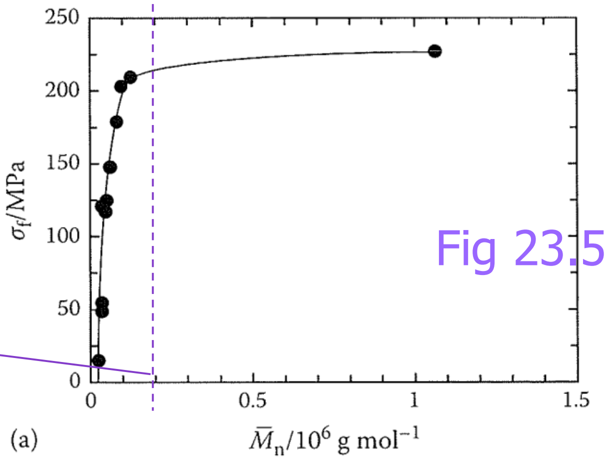


Fig 23.5

Brittle fracture

- theoretical (tensile) strength of solids (by Griffith)
  - $\sigma_t \approx \frac{E}{10}$ ← for interatomic separation pp557-558
    - whiskers, σ_u or $\sigma_f \approx E/10$
    - polymer single crystals, σ_u or $\sigma_f \approx E/40$
- for (isotropic glassy unfilled) polymers,
  - $\sigma_f < E/100 < \sigma_{theo}$
    - $E = 1 – 3$ GPa, $\sigma_f < 100$ MPa
  - due to flaw [crack, notch, or inclusion], which cause
    - stress concentration and
    - plastic constraint

σ_t = tensile strength
σ_u = ultimate stress
σ_f = fracture stress
σ_c = craze stress
$\sigma_u = \sigma_f = \sigma_c$ if brittle

- stress concentration
  - Ahead of crack tip, stress is larger than the applied stress σ_0

$$\sigma = \sigma_0\left(1+\frac{2a}{b}\right)$$

  - circular crack [a=b], $\sigma = 3\,\sigma_0$
  - crack-tip radius $\rho = \frac{b^2}{a}$

$$\sigma = \sigma_0\left[1+2\left(\frac{a}{\rho}\right)^{1/2}\right] \underset{\uparrow}{=} \sigma_0 2\left(\frac{a}{\rho}\right)^{1/2}$$

If the crack is long and sharp ($a \gg \rho$)

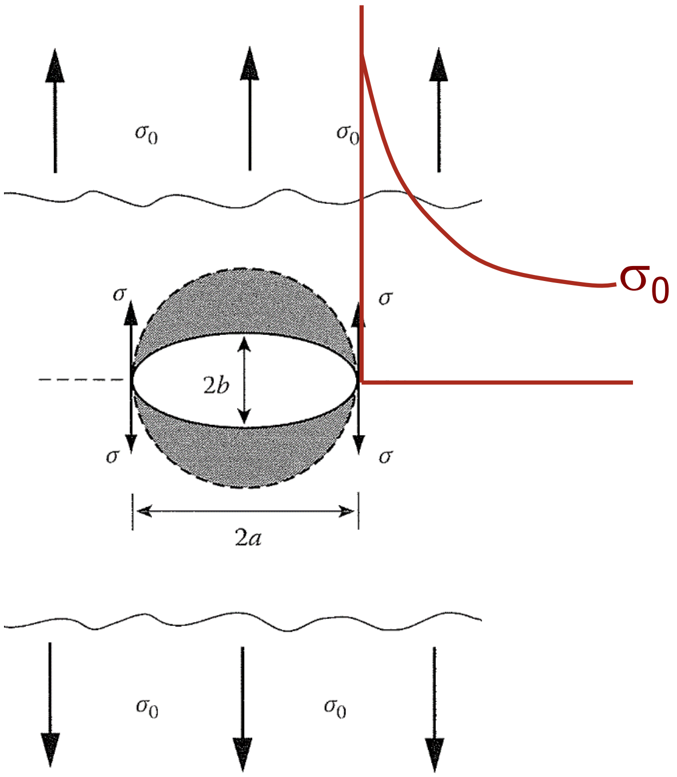


Fig 23.6 p562

Fracture mechanics

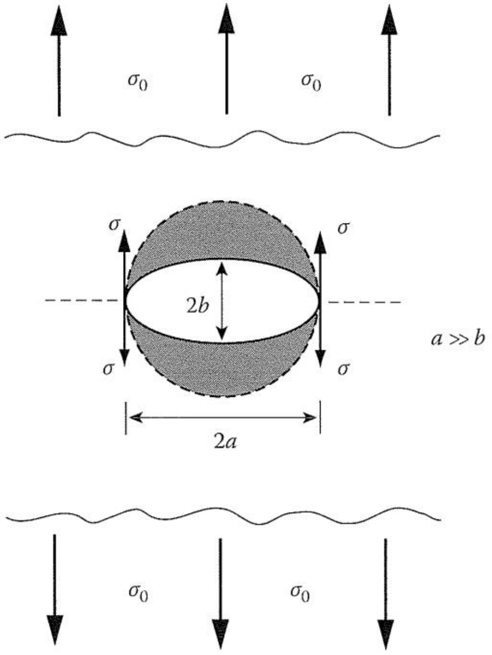
- energy balance approach
  - specimen with crack length 2a
  - Crack grows when released (elastic) strain energy by stress [$\sigma^2\pi a^2/2E$] is greater than created surface energy [$4a\gamma$]
  - Griffith (brittle) fracture criterion

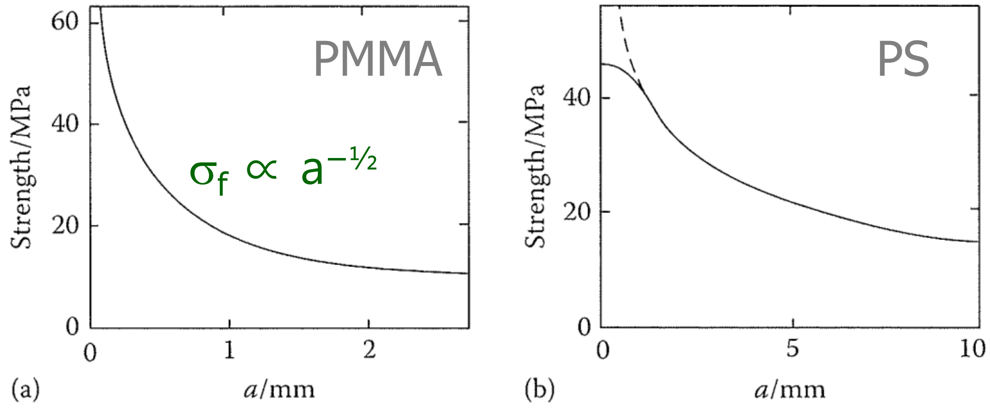
LEFM [linear elastic FM]

$$\sigma_f = \left(\frac{2E\gamma}{\pi a}\right)^{1/2} \qquad \sigma_f = \left[\frac{2E\gamma}{\pi(1-v^2)a}\right]^{1/2}$$

plane σ

plane e





$\sigma_f \propto a^{-1/2}$

Fig 23.7

- energy balance approach (cont'd)
  - for polymers
    - γ from exp't = ~ 1 J/m^2
    - γ from Griffith criterion = ~ 1,000 J/m^2
      - high γ ← high σ_f
    - high σ_f ← other process than elastic = plastic deformation at crack tip
      - local yielding ~ still brittle fracture
  - replacing 2γ with G_c

$$\sigma_f = \left(\frac{2E\gamma}{\pi a}\right)^{1/2}$$

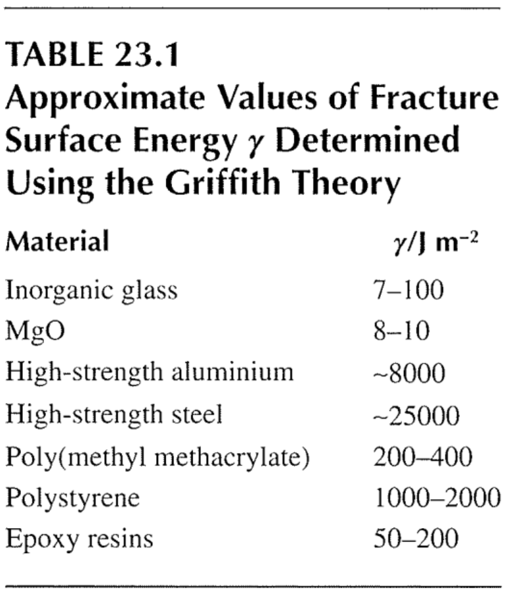


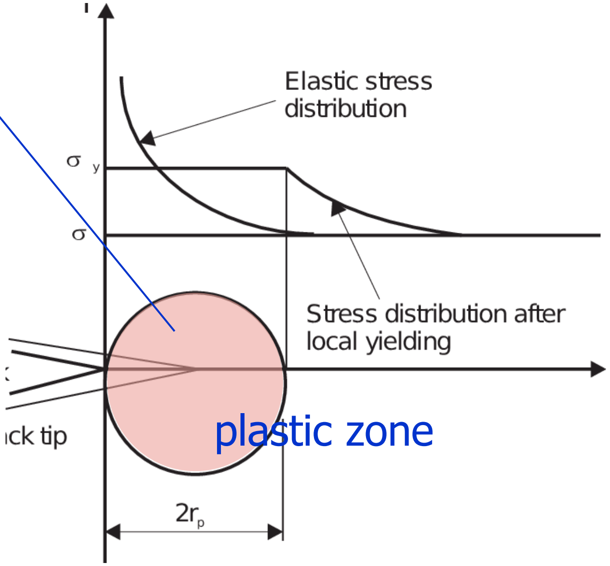
TABLE 23.1
Approximate Values of Fracture Surface Energy γ Determined Using the Griffith Theory

Material	γ/J m^{-2}
Inorganic glass	7–100
MgO	8–10
High-strength aluminium	~8000
High-strength steel	~25000
Poly(methyl methacrylate)	200–400
Polystyrene	1000–2000
Epoxy resins	50–200

$$\sigma_f = \left(\frac{EG_c}{\pi a}\right)^{1/2}$$

Irwin's modification of Griffith criterion

- G_c = critical strain energy release rate = 'fracture energy' [J/m^2]



- ❑ stress intensity factor approach
  - ❑ fracture when $\sigma(\pi a)^{1/2} > (EG_c)^{1/2}$

$$\sigma_f = \left(\frac{EG_c}{\pi a}\right)^{1/2}$$

  - ❑ stress intensity factor K

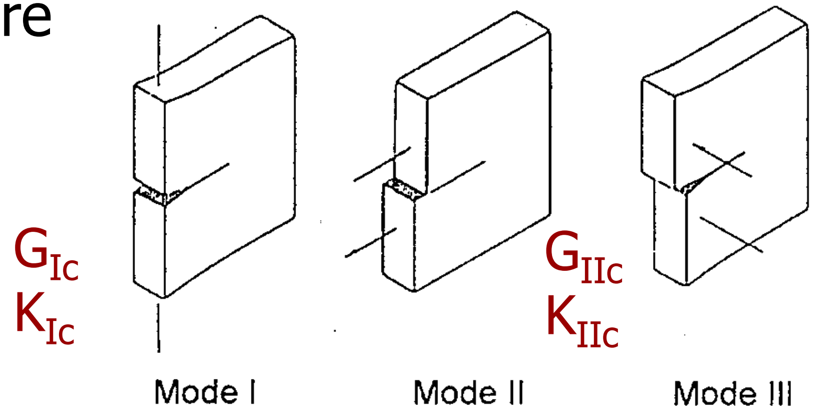
$$K = \sigma\sqrt{\pi a}$$

  - ❑ crack propagates when K reaches K_c

$$K_c = \sqrt{EG_c}$$

    - K_c = critical stress intensity factor
      = 'fracture toughness' [(파괴)강인성] [MPa m$^{1/2}$]

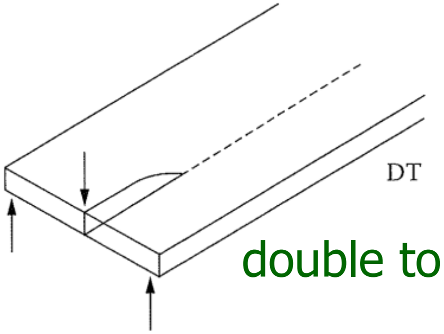
➢ 3 modes of fracture



Fracture testing

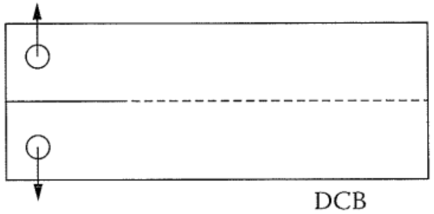
- specimen

single-edge notched tension

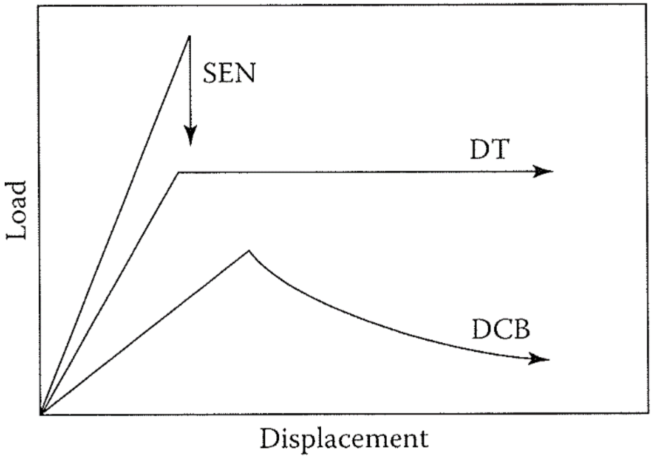


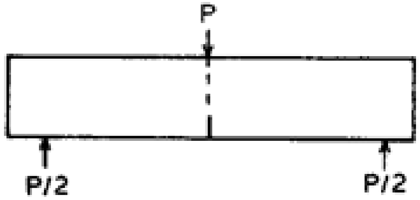
double torsion

Fig 23.8



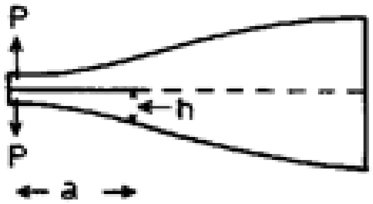
double cantilever beam



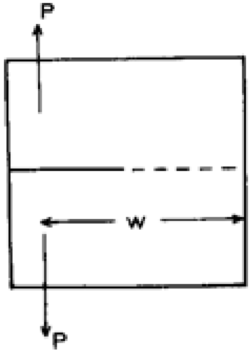


Three-point bend

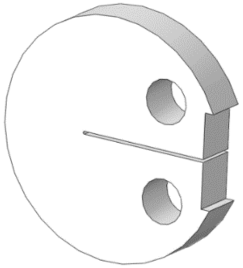
SEN-3PB



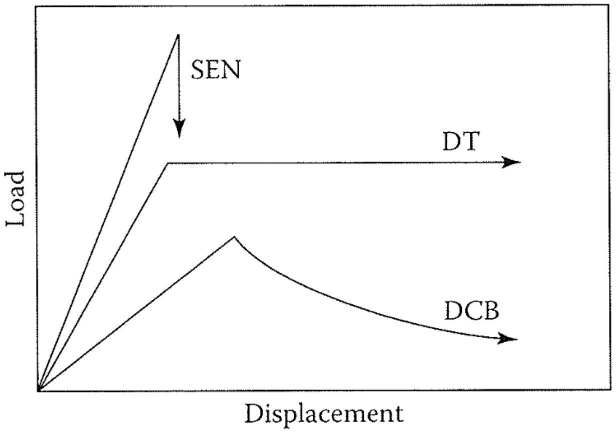
Tapered-double-cantilever-beam



Compact-tension



- load (f) → K



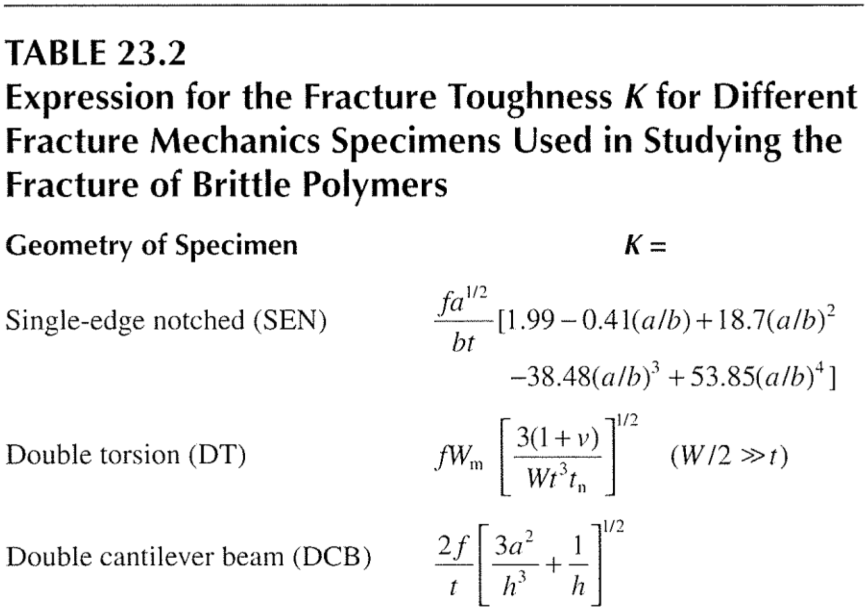
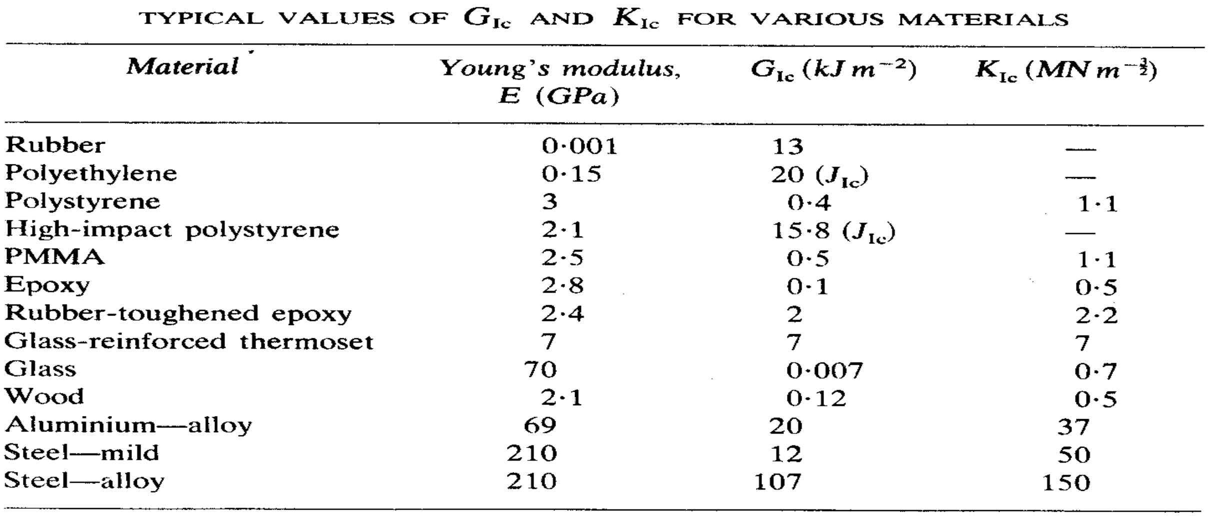


TABLE 23.2

Expression for the Fracture Toughness *K* for Different Fracture Mechanics Specimens Used in Studying the Fracture of Brittle Polymers

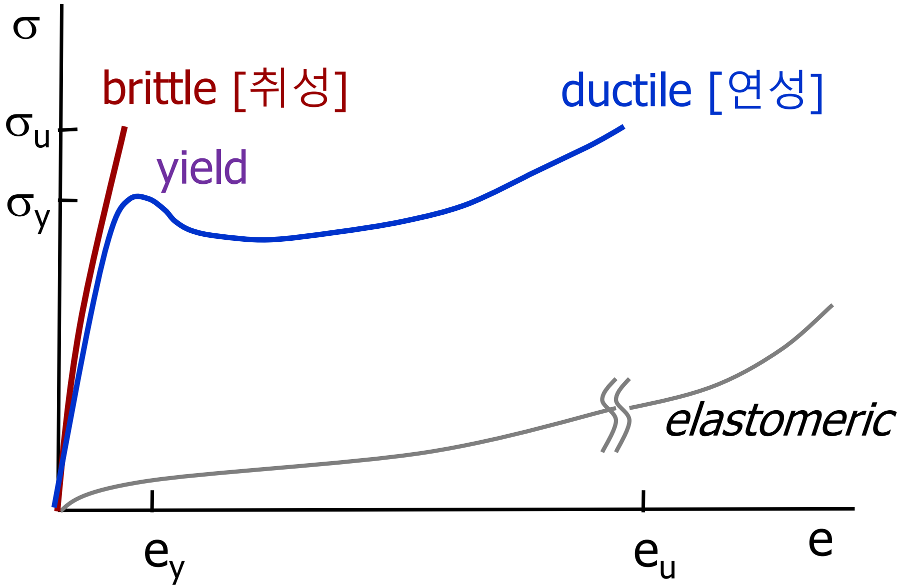
Geometry of Specimen	*K* =
Single-edge notched (SEN)	$\frac{fa^{1/2}}{bt}[1.99-0.41(a/b)+18.7(a/b)^2 -38.48(a/b)^3+53.85(a/b)^4]$
Double torsion (DT)	$fW_m\left[\frac{3(1+\nu)}{Wt^3t_n}\right]^{1/2}$ $(W/2 \gg t)$
Double cantilever beam (DCB)	$\frac{2f}{t}\left[\frac{3a^2}{h^3}+\frac{1}{h}\right]^{1/2}$


TYPICAL VALUES OF G_{Ic} AND K_{Ic} FOR VARIOUS MATERIALS

Material	*Young's modulus, E (GPa)*	G_{Ic} *(kJ m^{-2})*	K_{Ic} *(MN m$^{-\frac{3}{2}}$)*
Rubber	0·001	13	—
Polyethylene	0·15	20 (J_{Ic})	—
Polystyrene	3	0·4	1·1
High-impact polystyrene	2·1	15·8 (J_{Ic})	—
PMMA	2·5	0·5	1·1
Epoxy	2·8	0·1	0·5
Rubber-toughened epoxy	2·4	2	2·2
Glass-reinforced thermoset	7	7	7
Glass	70	0·007	0·7
Wood	2·1	0·12	0·5
Aluminium—alloy	69	20	37
Steel—mild	210	12	50
Steel—alloy	210	107	150

Ductile fracture

- failure after general yielding
- fracture with large plastic zone



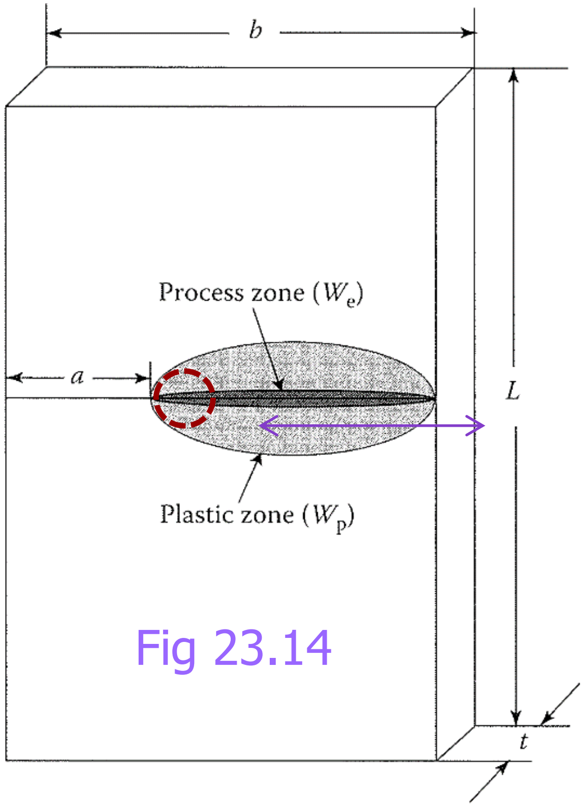


Fig 23.14

Ductile-brittle transition

- yield to ductile failure
  craze to brittle fracture
- Both σ_y and σ_c [σ_b] are dependent on temperature, strain rate, --.

- temperature

T_b = d-b transition Temp

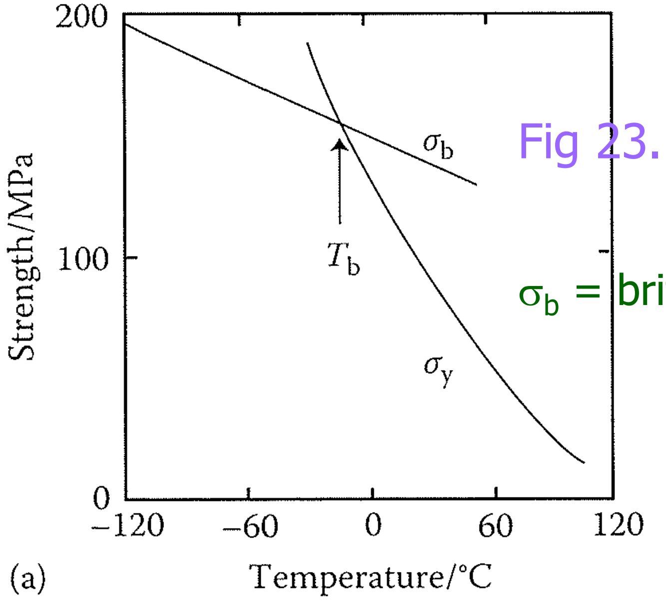
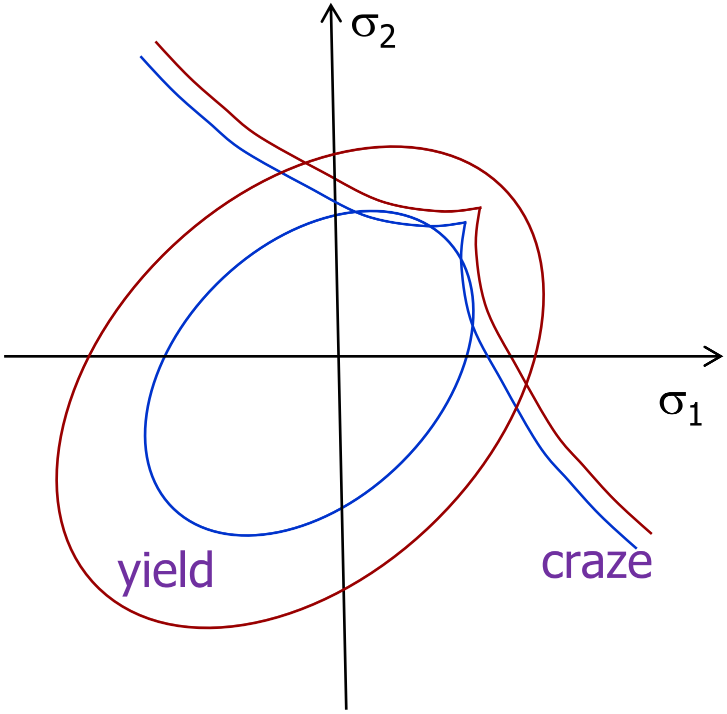


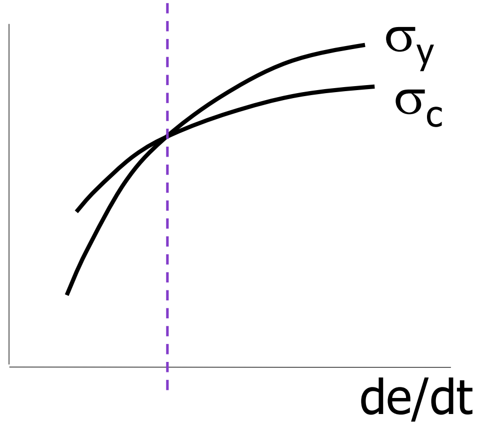
Fig 23.18(a)

σ_b = brittle stress = σ_c



high T, low de/dt
low T, high de/dt

- strain rate



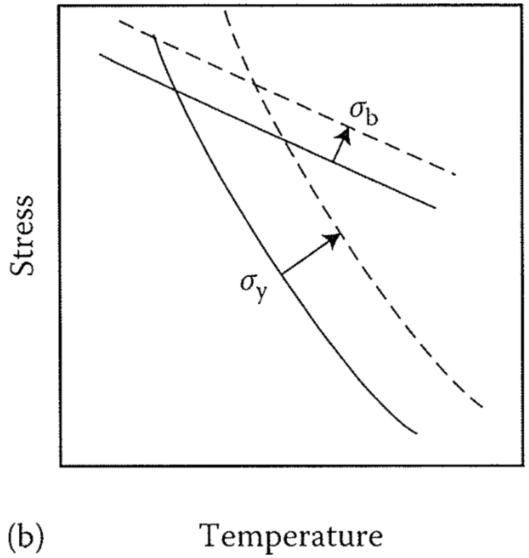
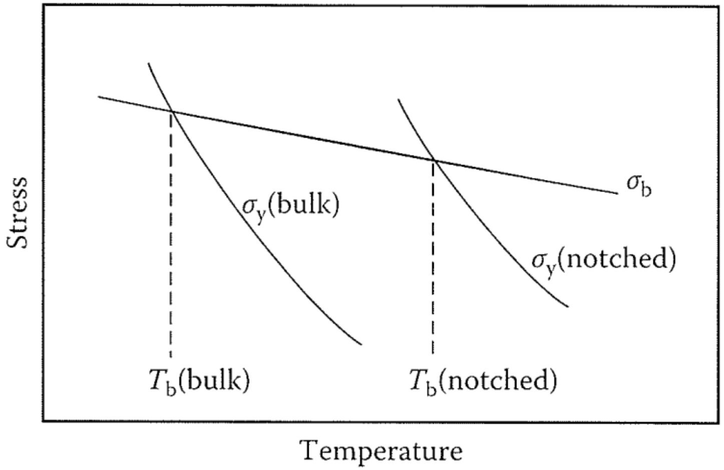
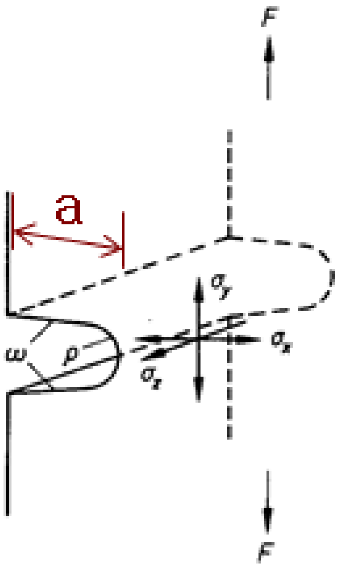


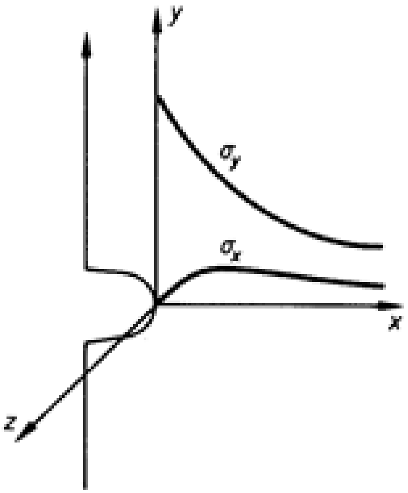
Fig 23.18(b)

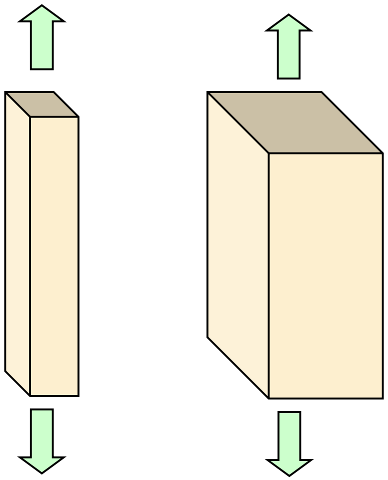
  - T_b increases as strain rate increases.
- surface notch, crack, scratch
  - notch brittleness [plastic constraint]
  - notch → triaxial stress state ahead → σ_y ↑ → T_b ↑



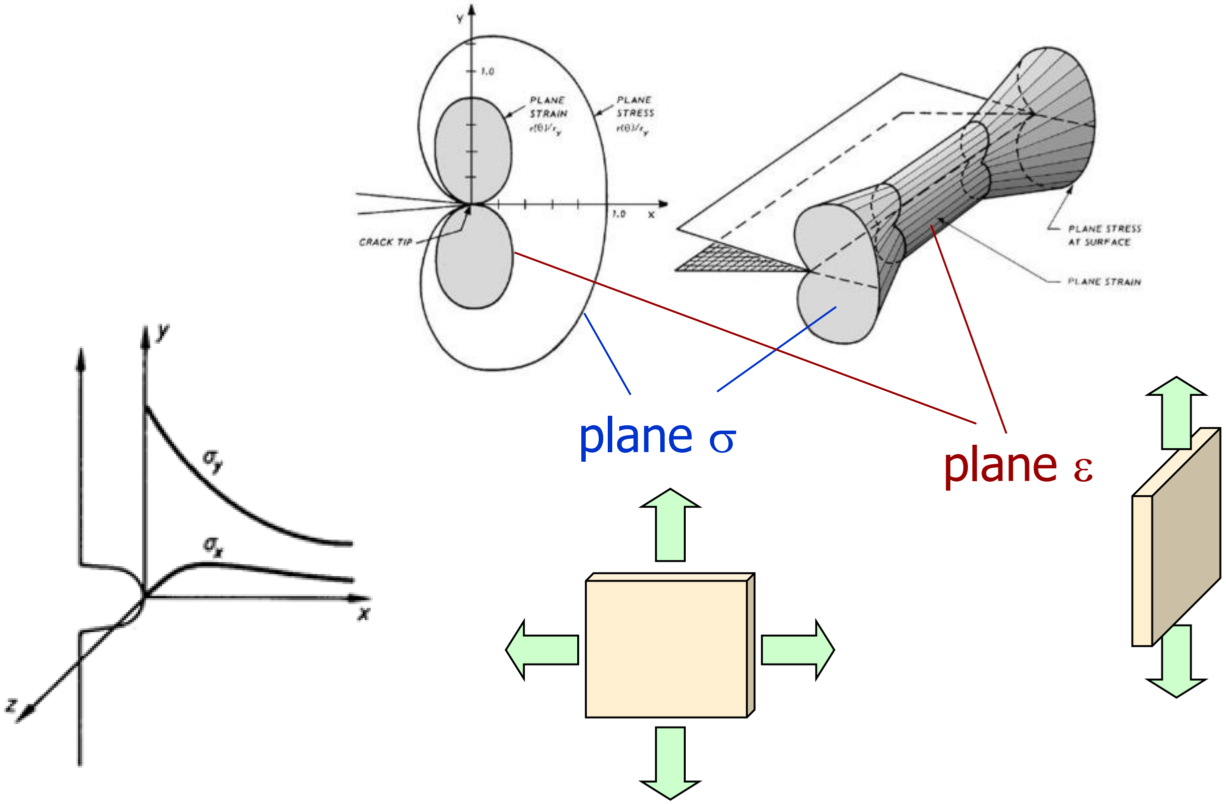
- plastic constraint
  - Ahead of crack tip, there exists triaxial stress state.
    - $\sigma_1 > 0$ (applied), σ_2 and $\sigma_3 > 0$ (due to crack)
  - triaxiality → yield at higher stress ← $\sigma_s = \sigma_1 - \sigma_3$
  - plastic deformation constrained
  - craze rather than yield → brittle fracture







- d-b transition with thickness of specimen
  - as thickness ↑
  - plane stress [ductile] to plane strain [brittle] transition



Impact strength

- testing method
  - flexed beam impact test
    - Charpy, Izod
  - falling weight impact test
  - tensile impact test
- impact strength [IS, 충격강도]
  - energy absorbed per unit area (J/m^2) or unit length (J/m)
    - energy rather than strength
  - related to Gc

$$U_S = G_c t b Z$$

    - but <u>not</u> this quantitative
    - G_{Ic} (and K_{Ic}) are material properties: IS is not. ← depends on geometry

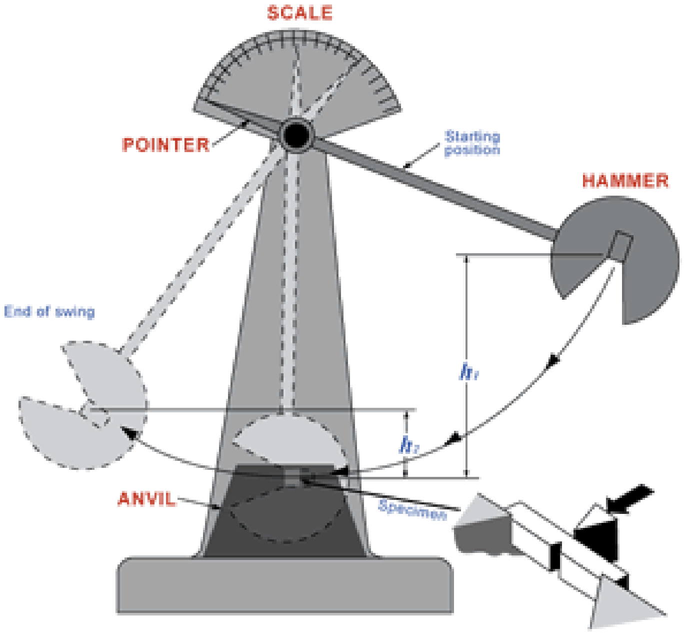
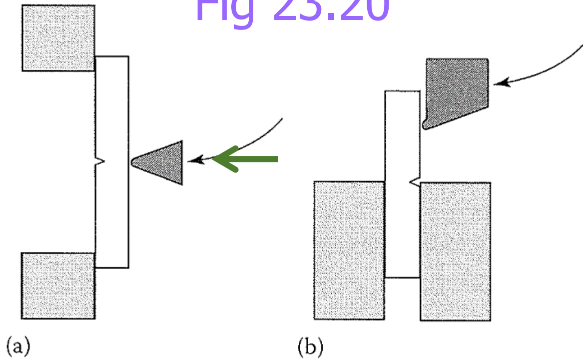


Fig 23.20

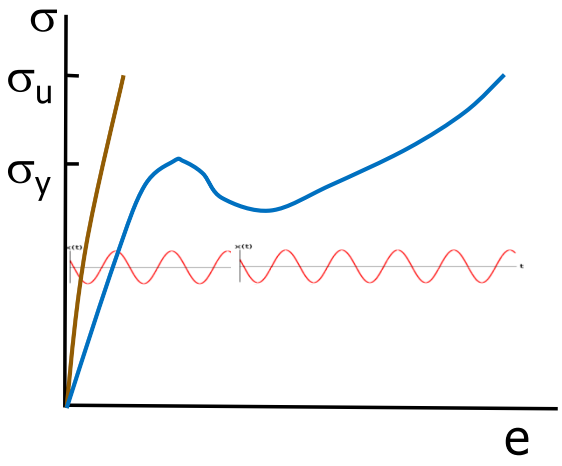


Charpy

Izod

Fatigue

- Upon cyclic loading [oscillation],
  - materials fail [fracture] at stress level well below they can withstand under static loading (usually YS or TS).
  - very common in metal



- S-N curve
  - stress vs # of cycles to fracture
  - fatigue strength or 'endurance limit'

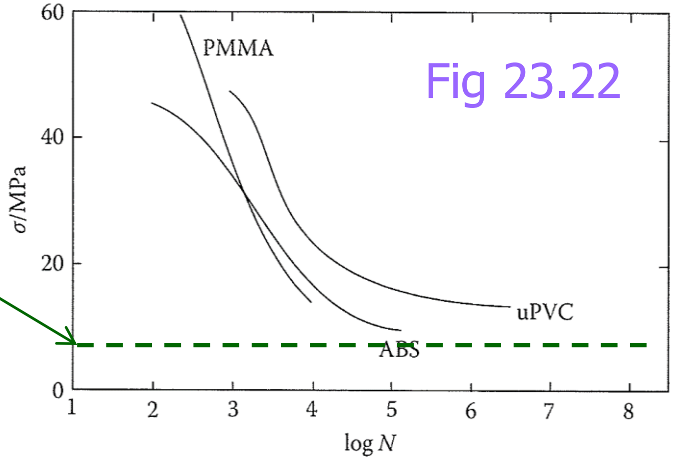


Fig 23.22

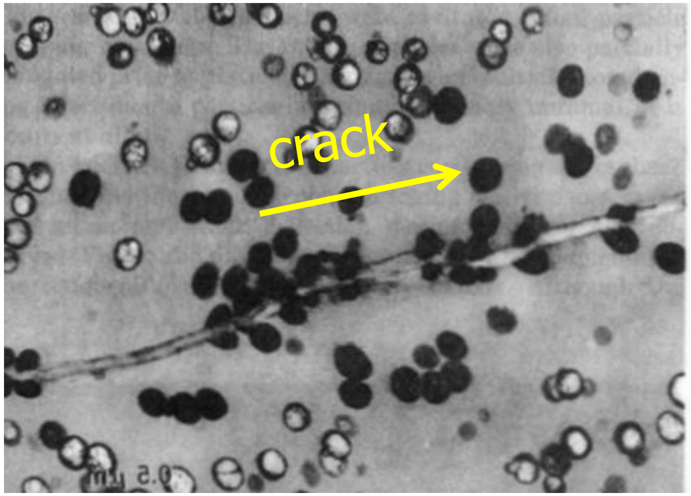
- fatigue crack propagation
  - Paris equation $$\frac{da}{dN} = C(\Delta K)^m$$
    - $\Delta K \propto \Delta\sigma$
    - lower m for tough polymers? not really Fig 23.23
      - PS, PMMA, PC

Toughening

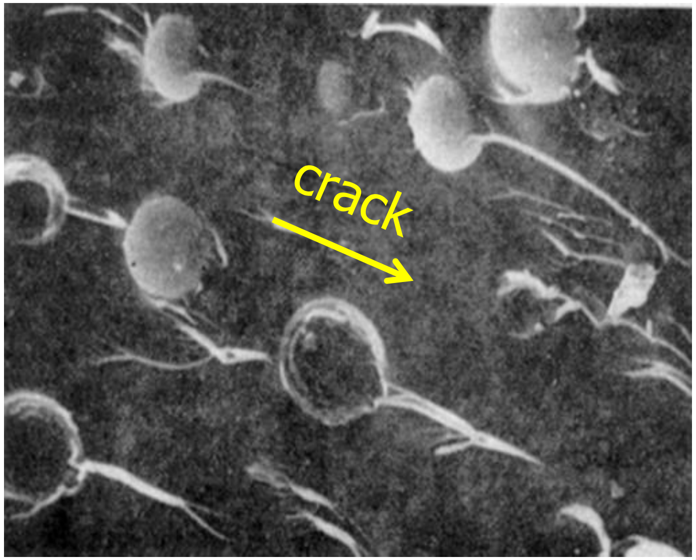
- dream: strength of steel with resilience of rubber
- goal: enhancing the ability to resist crack propagation
- toughening = introducing 2nd phase that
  - enlarge the volume of energy absorption, or
  - limit the crack growth by increasing # of site of crazing or yielding
- methods
  - rubber toughening
    - large energy absorption, modulus drop
    - HIPS, ABS, toughened epoxy, etc
  - thermoplastic toughening
    - small energy absorption, no modulus drop
    - PC/ABS, PC/PBT, Nylon/PPO, etc

Toughening mechanisms

- deformation and rupture of rubber particles
  - relatively small increase in toughness



- crack pinning
  - increasing surface area
  - tortuous path



- multiple crazing
  - particles initiate and stop crazes
  - stress-whitening observed
  - HIPS

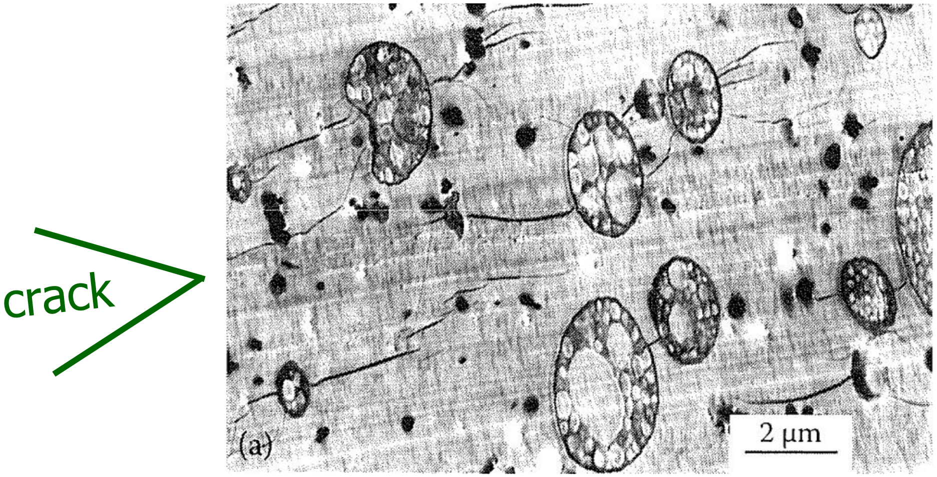


Fig 23.28

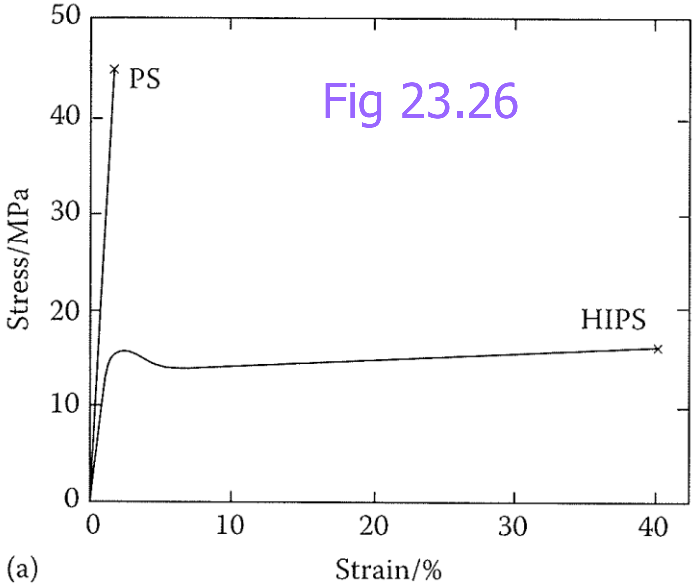
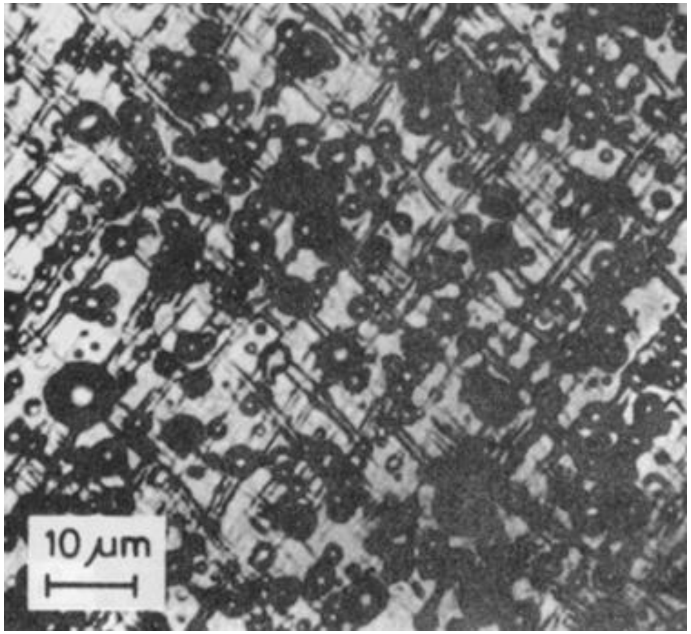


Fig 23.26

- cavitation and shear yielding
  - particles debond or cavitate
  - removing triaxiality
    - removing hydrostatic component
  - inducing yielding of matrix
  - necking observed
  - toughened PVC

crack



- crazing and shear yielding
  - whitening and necking
  - ABS

Factors governing toughness

- matrix
  - degree of crosslinking
  - entanglement density
  - T_g
  - yield strength
- particle
  - content [volume fraction]
  - size
  - size distribution
  - T_g
  - adhesion to matrix
  - morphology

Fig 23.25